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# THREE DIMENSIONAL SIMULATION OF THE BANEBERRY NUCLEAR EVENT

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**Abstract.** Baneberry, a 10-kiloton nuclear event, was detonated at a depth of 278 m at the Nevada Test Site on December 18, 1970. Shortly after detonation, radioactive gases emanating from the cavity were released into the atmosphere through a shock-induced fissure near surface ground zero. Extensive geophysical investigations, coupled with a series of 1D and 2D computational studies were used to reconstruct the sequence of events that led to the catastrophic failure. However, the geological profile of the Baneberry site is complex and inherently three-dimensional, which meant that some geological features had to be simplified or ignored in the 2D simulations. This left open the possibility that features unaccounted for in the 2D simulations could have had an important influence on the eventual containment failure of the Baneberry event. This paper presents results from a high-fidelity 3D Baneberry simulation based on the most accurate geologic and geophysical data available. The results are compared with available data, and contrasted against the results of the previous 2D computational studies.

## INTRODUCTION

Baneberry was a 10-kiloton underground nuclear test (UGT) conducted at a depth of 278 m in hole U8d at the Nevada Test Site on December 18, 1970. About 3.5 minutes after detonation, radioactive gases and debris began venting through a fissure that had occurred earlier near surface ground zero [1]. Extensive 2D computational studies of the event were performed [2]. Unfortunately, the Baneberry site has a complex geology and many simplifications had to be made in order to fulfill the geometric assumptions of 2D calculations. Recent advances in computational capabilities and computer codes made it possible to perform 3D simulations of the event using all the available geological data. The investigation was performed using the LLNL code GEODYN, a parallel transient Eulerian finite volume code with constitutive models that are well suited for analyzing the dynamic response of geologic media. The calculation demonstrated that interaction of the shock wave with several undesirable features of the Baneberry site led to the formation of a continuous

damaged region that connected the working point to the surface fissure where the vent was first observed. This damaged region is a likely path for the radioactive gases emanating from the cavity to reach the surface.

## BANEBERRY GEOLOGY

A high-resolution model of the Baneberry geology is shown in Figure 1. This model was constructed using EarthVision®, a commercial software package for 3D geologic model building and visualization. The model was developed based on information from the boreholes represented by the blue lines in Fig. 1. Some of these boreholes were pre-shot exploratory boreholes while others were associated with neighboring UGTs that preceded Baneberry. Still others were post-shot boreholes drilled to collect data to aid in the investigation into the cause of the Baneberry containment failure. The model shown in Fig. 1 is the most accurate geologic model available of the Baneberry site, and includes features of the site

believed to have contributed to the formation of the fissure:

- Three major faults with appreciable differential displacement near the working point (WP);
- Multilayered geology containing two layers of porous alluvium, a tuff layer and a hard paleozoic layer;
- A clay-altered tuff region in the vicinity of the WP. This region was modeled as two discrete regions with 50% and 20% clay content, with the 50% clayey region fully contained within the 20% region.

The EarthVision® geologic model was remapped on a rectangular grid with volume fractions to perform the 3D Baneberry containment calculation.

### NUMERICAL METHOD

The 3D Baneberry simulations were performed using GEODYN, a 3D Eulerian Gudonov code with adaptive mesh refinement capabilities. It is a parallel code that has been used on many of LLNL's ASCI computing platforms to simulate a

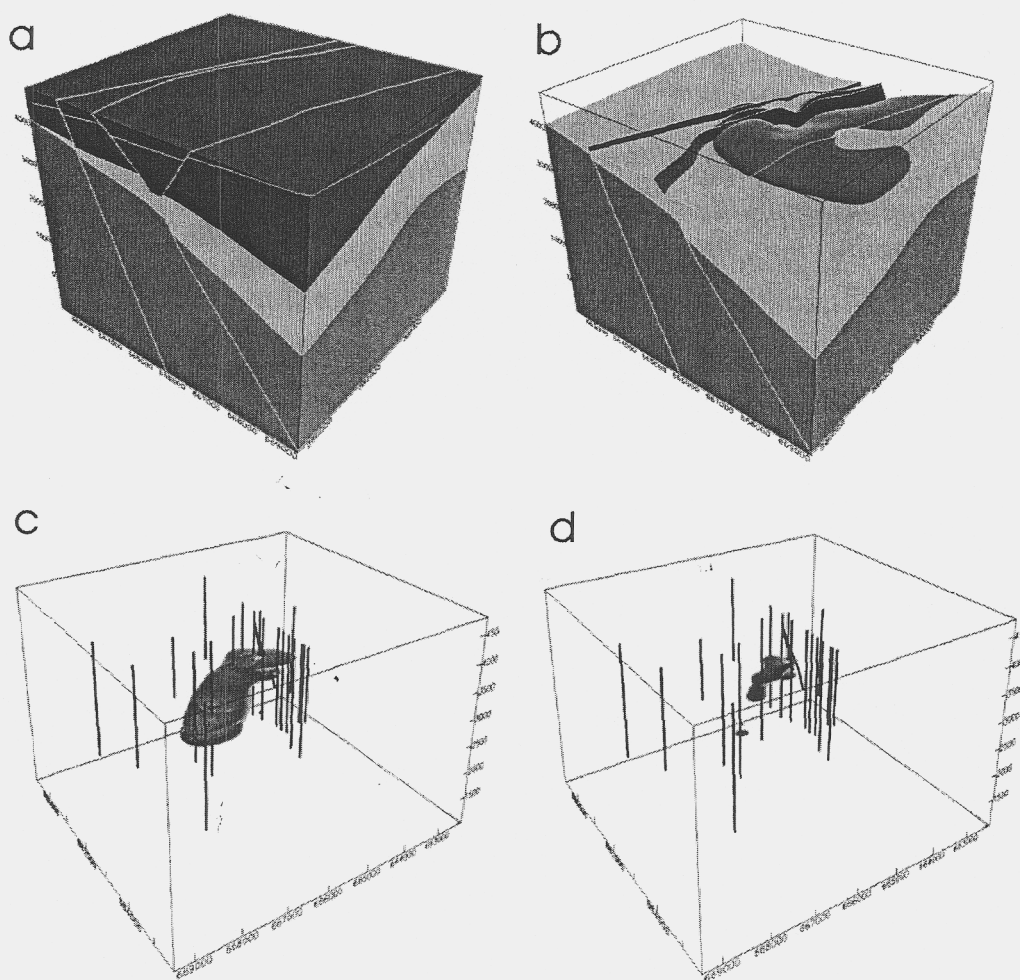


FIGURE 1. EarthVision® geologic model of Baneberry site. a) Overall geology b) Geology with the top alluvium layer removed c) The layer of tuff with clay content greater than 20% d) The layer of tuff with clay content greater than 50%

wide range of problems involving the interaction of shock waves with geologic media. Among its many features, GEODYN includes a high order interface reconstruction algorithm, and an advanced thermodynamically consistent constitutive model that incorporates many of the salient features of the dynamic response of geologic media. Because it uses a Eulerian formulation, GEODYN is able to handle the severe material deformation in the near-source region. Material interfaces in the code are treated using a volume fraction approach with a piecewise linear interface reconstruction method. A high-order Godunov solver is used in single-material regions. Material strength is described within the framework of the general, fully nonlinear theory of plasticity. Porous compaction and dilatancy are also included in the formulation, which on the whole is thermomechanically consistent with the second law of thermodynamics. The code is implemented in the BoxLib framework originally developed at Berkeley National Laboratory. BoxLib provides a framework for efficient adaptive mesh refinement, and is fully capable of massively parallel execution.

## MATERIAL MODELS

Properties for the six different geologic materials in the simulation were taken from the work of Glenn et. al. [2]. The incipient porosity compaction model, pressure dependent yield surface and the equation of state were transferred unmodified. The main challenge was to adapt a directional tensile failure model with features similar to those of the model used in the 2D Lagrangian calculations. A model that uses explicit cracks to represent tensile failure, like the one used in the 2D Lagrangian simulations, is difficult to use in a Eulerian framework due to difficulties in advecting crack damage variables, including the orientation of the fracture triad. Hence a new model for directional tensile failure was developed within the framework of a properly invariant nonlinear thermomechanical theory [3]. The new model introduces a second order damage tensor, which admits damage-induced anisotropy, and allows weakening due to tension applied in one direction, without weakening to subsequent tension applied in perpendicular directions. This damage tensor can be advected using standard methods in computer

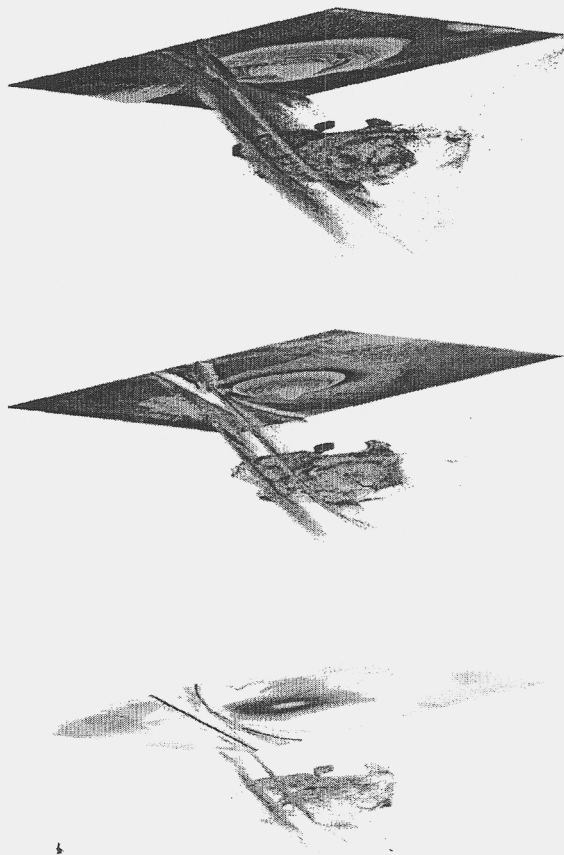
codes. Porosity is used as an isotropic measure of volumetric void strain and its evolution is influenced by tensile failure. The rate of dissipation due to directional tensile failure takes on a particularly simple form, which can be analyzed easily. Specifically, the model can be combined with general constitutive equations for porous compaction and dilation, as well as viscoplasticity. A robust non-iterative numerical scheme for integrating these evolution equations was implemented. An advantage of the new model is that it has a very limited number of parameters and they can be directly related to the parameters of the Lagrangian tensile failure model used in past containment calculations. This continuum multidirectional tensile damage model was successfully used to simulate damage development in an explosively loaded Danby marble specimen. The results of this study are presented in a companion paper in these proceedings [4].

## SIMULATION RESULTS

The Baneberry simulation described here was performed using 648 CPUs on the MCR cluster at LLNL. It took about three days, or approximately 50000 CPU hours, to complete the simulation. The computational grid consisted of 360x360x288 cells (about 38 million cells) with a 2.78-m spatial resolution. It took 3000 time steps to advance the calculation to 0.85 seconds, at which time the stress waves within the computational domain had attenuated sufficiently that all inelastic processes, including tensile damage accumulation, had ceased.

We interpret tensile damage as a necessary condition for the formation of the vent path. Figure 2 represents volume rendering of the eigenvalues of the damage tensor due to tensile failure. As the figure indicates, there are three regions where damage accumulation is most pronounced: the weak clayey region in the vicinity of the working point, the weak material within each of the three faults, and a cone-shaped spalled region near surface ground zero. These three damaged regions are connected to one another, thereby forming a continuous damaged region that connects the WP to the surface fissure where the radioactive release was first detected.

Within the context of the modeling approach presented here, tensile damage accumulation is a



**FIGURE 2.** Volume rendering of maximum, intermediate and minimum eigenvalues of the damage tensor at the end of the simulation. Vent path formation is clearly indicated.

necessary, but not necessarily a sufficient indicator of containment failure. Damaged regions are generally more porous and as such more permeable than the surrounding medium. However, when a damaged zone is subjected to compression normal to the crack surface, recompaction occurs and the once permeable damaged zone can become much less permeable. For this reason, a complete assessment of containment requires a time-resolved examination of the stress field in the region connecting the WP to the ground surface, in addition to an examination of the evolution of damage. Such an analysis is complex and requires advanced visualization tools that are currently under development. We expect these tools to reach

a state of maturity that allows for a complete containment assessment in the near future. In the mean time, a limited analysis of the stress field around the Baneberry cavity has been performed. This analysis indicates a loss of spherical symmetry early in the simulation due to wave reflections in the region near the cavity. The reflections are most prominent at the interface between the hard Paleozoic layer and the much weaker tuffaceous layer, which also has a much lower impedance than the Paleozoic. The lack of symmetry, especially at late time, inhibits the formation of a residual compressive stress field around the cavity. Such a stress field, generally called a stress cage, has been observed experimentally, and is viewed as being an important component of a well contained UGT [1]. The results of the present 3D Baneberry simulation do not support the formation of a residual compressive stress field around the WP. In this regard the results of the 3D simulation are also consistent with those obtained earlier in the 2D computational examination of the Baneberry event [2].

#### ACKNOWLEDGMENTS

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